

VI. Zagami

Basalt, 18 kg

seen to fall



Figure VI-1. Photograph of sawn surface of Zagami meteorite kindly provided by Robert Haag. Note the variation in texture and the thin veins of black glass. Sample about 12 cm across.

Introduction

Zagami fell on October 3, 1962 about 0.75 miles from Zagami Rock, Katsina Province, Nigeria (Graham *et al.* 1985). In 1985, the main mass was with the Geological Survey of Nigeria in Kaduna. About 1988, Robert Haag (meteorite dealer) obtained a large piece of Zagami. Since then, the whole specimen has apparently been cut up and “distributed” (see *Processing*).

Both Shergotty and Zagami are texturally and mineralogically similar to terrestrial diabbases (although plagioclase has been shocked to maskelynite), but quite

distinct petrologically and chemically from the rest of the basaltic achondrites (Stolper *et al.* 1979). From what is now known about Zagami, it appears to have been made up of three related basaltic lithologies and minor shock-melted glass (McCoy *et al.* 1999).

Zagami was the second meteorite found to contain a significant amount of trapped Martian atmosphere (Marti *et al.* 1995). Thin veins of black glass were apparently formed by “shear melting during shock” (Langenhorst and Poirier 2000), and these apparently contain relic high-pressure phases (see section on Shock



Figure VI-2. Close-up photo of Zagami illustrating basaltic texture with alignment of pyroxene grains. Field of view is 1 cm. Photo courtesy L. Nyquist, NASA # S94-45980.

Effects).

Treiman (1993b) noted the apparent coincidence of the falls for Zagami and Chassigny, both on October 3 (different years). However, the cosmic-ray exposure ages are different for these two rocks.

Petrography

Zagami is apparently heterogeneous containing several different lithologies (figure VI-1). The normal Zagami lithology (NZ) is a basalt similar to Shergotty (Stolper and McSween 1979; McCoy *et al.* 1992, 1999). In addition, McCoy *et al.* (1995) have studied a dark-

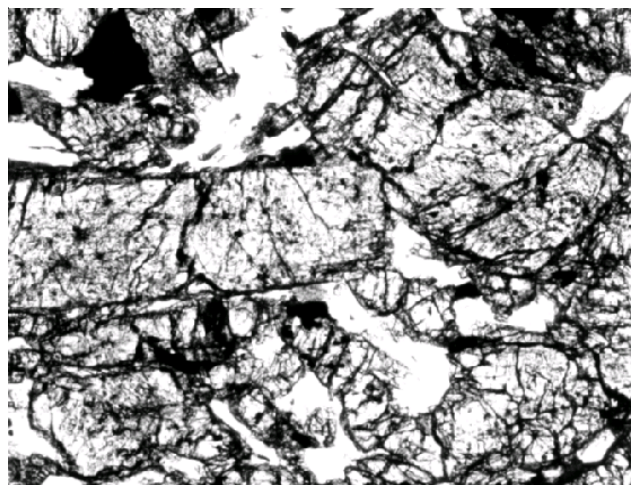


Figure VI-3. Photomicrograph of thin section of Zagami illustrating coarse-grained basaltic texture. Thin section #991 from University of New Mexico. Field of view 2.2 mm.

mottled-lithology (DML) which makes up ~ 20 % of the large specimen obtained by R. Haag. According to McCoy *et al.*, the DML lithology is separated from the NZ lithology along a sharp, but sometimes irregular boundary (figure VI-1) and is found to contain pockets of shock-melt found to contain Martian atmosphere (Marti *et al.* 1995). A centimeter-sized piece of distinctly different, Fe-rich material (described below), obtained from David New (see Agerkvist and Vistisen, 1993), was originally studied by Vistisen *et al.* (1992), and again by McCoy *et al.* (1993), Wadhwa *et al.* (1993), McCoy *et al.* (1995, 1999).

Normal Zagami exhibits a foliated texture produced by preferential orientation of pyroxene prisms and maskelynite grains (figure VI-2)(Stolper and McSween 1979; McCoy *et al.* 1992). It is made up of two portions with different grain size — an average grain size of 0.24 mm for the “fine-grain” portion and 0.36 mm for the “coarse-grained” portion (figures VI-3 and VI-4). The NZ portion of Zagami is cross-cut by glass veins

Mineralogical Mode

	Stolper & McSween 1979		McCoy <i>et al.</i> 1992				McCoy <i>et al.</i> 1993
			<i>fine grain</i>		<i>coarse grain</i>		<i>DN lithology</i>
pyroxene	76.3	69.7	77.7	74.3	76.0	80.4	13.6
maskelynite	18.8	24.7	17.6	18.8	18.6	10.3	18
mesostasis	1.7	2.6	1.8	3.0	2.1	3.7	8.1
oxides	2.7	2.8	1.5	1.8	2.0	2.6	5.9
sulfides	0.5	0.2	0.6	0.4	0.4	0.6	1.6
phosphates			0.5	0.6	0.5	1.3	11.4
shock melt			0.1	0.9	0.3	0.9	
fayalite-rich intergrowth						39.9	

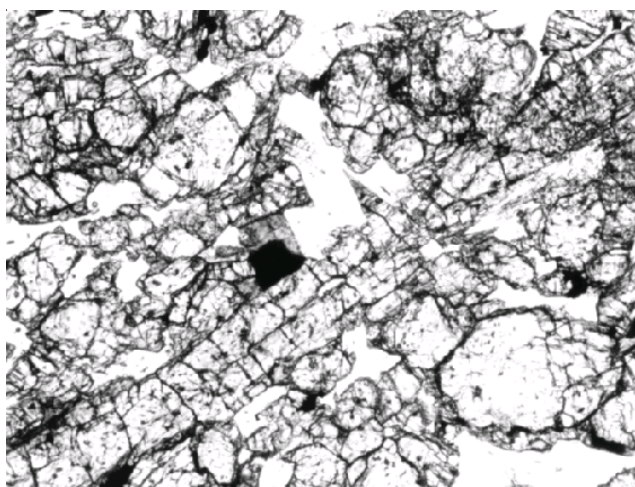


Figure VI-4. Photomicrograph of thin section of Zagami illustrating fine-grained basaltic texture. Thin section #999 from University of New Mexico. Field of view 2.2 mm.

of shock-melt that seem to follow the alignment of pyroxene laths (McCoy *et al.* 1992; Wadhwa *et al.* 1993). As in Shergotty, plagioclase has been converted to maskelynite (*or plagioclase glass*) by shock (Mikouchi *et al.* 1999; Langenhorst and Poirier 2000; Malavergne *et al.* 2001).

The Fe-rich, DN lithology of Zagami has been described as a residual melt (McCoy *et al.* 1993; Wadhwa *et al.* 1993). McCoy *et al.* describe pigeonite, plagioclase and phosphates as phenocryst phases in DN. Although augite occurs as phenocrysts in NZ, it does not in DN. The compositions of the phases in DN extend the range of composition of phases found in NZ to higher Fe and higher Na. There is also more whitlockite in DN lithology than in NZ and there are minor, relatively large, fluorapatite crystals in DN. Within the DN lithology, there are olivine-bearing intergrowths containing fayalite, Fe-rich augite and K-rich mesostasis.

Magmatic melt inclusions are found in the Mg-rich cores of the pigeonite grains (Treiman 1983, 1985; McCoy *et al.* 1992). Several of these melt inclusions include amphibole (see below).

Mineral Chemistry

Pyroxene: Easton and Elliot (1977) reported the compositions of pyroxene separates from Zagami. Stolper and McSween (1979), Mikouchi *et al.* (1999) and McCoy *et al.* (1999) have studied the pyroxene zoning (figure VI-5) and found it nearly identical to that of pyroxenes in Shergotty. Brearley (1991) studied

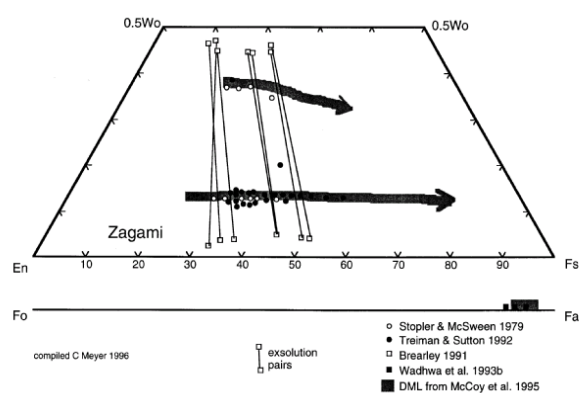


Figure VI-5. Composition diagram for pyroxene and olivine in Zagami meteorite. Data compiled from various sources. Crystallization trends and exsolution pairs indicated.

the subsolidus exsolution and microstructure of pyroxenes in Zagami. Treiman and Sutton (1992) and Shearer and Brearley (1992) studied the cores and rims of Zagami pyroxenes by synchrotron and ion microprobe techniques. Wadhwa *et al.* (1994a) determined the REE and minor element contents (Y, Sc, Ti, Cr, and Zr) of pyroxenes. The high-Ca pyroxenes contain about 10X REE abundance compared to low-Ca pyroxene, but with similar LREE depleted pattern. Lentz *et al.* (2002) reported Li, Be and B in pyroxene.

Feldspars: Easton and Elliot (1977) reported the composition of “feldspar/glass” in Zagami as $An_{51}Ab_{46}Or_2$. Stolper *et al.* (1979) determined that individual maskelynite grains are zoned from $An_{57}Ab_{42}Or_1$ to $An_{43}Ab_{53}Or_4$. Langenhorst *et al.* (1991) studied the index of refraction and composition to determine the shock pressure. Jones *et al.* (1985b) studied the zoning of minor elements in maskelynite with a proton microprobe technique. Mikouchi *et al.* (1998) and McCoy *et al.* (1999) found that Zagami maskelynite was not a diaplectic glass, but was a “melt glass” (see also Chen and El Goresy, 2000). Lentz *et al.* (2002) reported Li, Be and B in plagioclase.

Orthoclase-rich feldspar ($Or_{73}Ab_{22}$) is also present in both K-rich mesostasis and in fayalite intergrowths in portions of Zagami (McCoy *et al.* 1999). Possibly related, are reports of minute grains of $KAlSi_3O_8$ hollandite (a phase requiring high pressure origin) in shock-melted veins (Langenhorst and Poirier 2000).

Amphibole: Treiman (1985a) reported hydrous amphibole in melt inclusions in Zagami. One grain of

Table VI-1. Chemical composition of Zagami.

	Treiman 86	Laul 72	Easton 77	Burger 89	Smith 84	Shih 82	Ma 81	Ma 82	HaramuraStolper79	McCoy92
<i>weight</i>	<i>0.1-0.2 g</i>						<i>(Irving)</i>	<i>40 mg</i>		
SiO ₂ %			50.9 (d)					50.52 (d)	50.8 (e)	51.2
TiO ₂			0.73 (d)	0.77 (a)	0.8 (b)			0.8 (b)	0.84 (d)	0.81
Al ₂ O ₃			5.7 (d)		6.4 (b)			6.4 (b)	6.27 (d)	6.19
FeO			17.3 (d)		19 (b)			19 (b)	18.03 (d)	18.2
MnO			0.5 (d)		0.5 (b)			0.502 (b)	0.44 (d)	0.55
CaO			10.5 (d)		10.6 (b)			10.6 (b)	9.57 (d)	10.7
MgO			11.4 (d)		11.1 (b)			11.1 (b)	12.14 (d)	10.4
Na ₂ O			1.2 (d)		1.21 (b)			1.21 (b)	0.13 (d)	1.29
K ₂ O			0.1 (d)		0.14 (b)			0.14 (b)	0.08 (d)	0.13
P ₂ O ₃			0.48 (d)					0.46 (d)		0.58
sum			98.81					98.45	98.67	100.05
Li ppm						3.82 (c)				
C										
F										
S										
Cl										
Sc					53 (b)		57 (b)	53 (b)		
V					312 (b)			312 (b)		
Cr			2600 (d)		1984 (b)			1984 (b)	1026 (d)	
Co					36 (a)		37 (b)	36 (b)		
Ni	90 (a)				50 (b)		67 (b)			
Cu										
Zn	63.8 (a)	55 (a)			62 (a)					
Ga					14 (a)					
Ge	0.78 (a)									
As					0.046 (a)					
Se	0.32 (a)	0.33 (a)			0.32 (a)					
Br	0.79 (a)									
Rb	9.56 (a)	6 (a)			5.7 (a)	5.69 (c)				
Sr					46	45.9 (c)				
Y				10.6 (a)						
Zr				58.2 (a)						
Nb										
Mo										
Pd ppb	1.79 (a)									
Ag ppb	14.2 (a)	37 (a)			31					
Cd ppb	179 (a)	71 (a)			61 (a)					
In ppb	26.6 (a)	22.2 (a)			22 (a)					
Sb ppb	5.2				12 (a)					
Te ppb	2.2 (a)				1 (a)					
I ppm										
Cs ppm	0.367 (a)	0.336 (a)			0.38 (a)					
Ba				27.4 (a)	25 (b)	25.3 (c)				
La					0.9 (b)	1.6 (c)	2.07 (b)	0.9 (b)		
Ce						3.75 (c)				
Pr										
Nd						2.89 (c)				
Sm					0.76 (b)	1.17 (c)	1.42 (b)	0.76 (b)		
Eu					0.44 (b)	0.476 (c)	0.51 (b)	0.44 (b)		
Gd										
Tb					0.22 (b)		0.34 (b)	0.22 (b)		
Dy					1.7 (b)	2.66 (c)		1.7 (b)		
Ho										
Er						1.6 (c)				
Tm										
Yb					0.98 (b)	1.38 (c)	1.45 (b)	0.98 (b)		
Lu					0.13 (b)	0.201 (c)	0.26 (b)	0.13 (b)		
Hf				1.6 (a)	1.7 (b)		1.9 (b)	1.7 (b)		
Ta				0.19 (a)	0.2 (b)		0.22 (b)	0.2 (b)		
W ppb				800 (a)						
Re ppb	0.035 (a)									
Os ppb	0.119 (a)									
Ir ppb	0.033 (a)	0.1 (a)								
Au ppb	1.76 (a)	2.1 (a)			2.2 (a)					
Tl ppb	11.7 (a)	11 (a)			12 (a)					
Bi ppb	1.64 (a)	1.1 (a)			5.1 (a)					
Th ppm										
U ppm	0.094 (a)				0.154 (a)		0.27 (b)			
<i>technique (a) RNAA, (b) INAA, (c) Isotope dilution mass spec., (d) wet, (e) elec. probe, fused sample</i>										

Table VI-1 (continued). Chemical Composition of Zagami.

<i>reference weight</i>	<i>Lodders 98 average</i>	<i>Barrat 2001 83 mg.</i>	<i>Kong 1999 39.5 mg.</i>	<i>Wang 98</i>	<i>Brandon 2000 2.052 g.</i>	<i>Blichert-Toft 99 102 mg. 156 mg.</i>		
SiO ₂	50.5							
TiO ₂	0.79	0.67	(a) 0.82	(c)				
Al ₂ O ₃	6.05	5.35	(a) 3.53	(c)				
FeO	18.1	19.1	(a) 18.78	(c)				
MnO	0.5	0.58	(a) 0.62	(c)				
CaO	10.5	8.35	(a) 9.63	(c)				
MgO	11.3	12.31	(a) 10.91	(c)				
Na ₂ O	1.23	1.1	(a) 1.08	(c)				
K ₂ O	0.14		0.17	(c)				
P ₂ O ₅	0.5							
<i>sum</i>	99.61							
Li ppm	2.9							
Sc	55	53	(b) 55.1	(c)				
V	312		259	(c)				
Cr	2260		1900	(c)				
Co	36	39.5	(b) 43.4	(c) 36	(d)			
Ni	48	101	(b) 111	(c)				
Cu		14	(b)					
Zn	60	59	(b) 79	(c) 62	(d)			
Ga	14	12.68	(b) 10.4	(c) 14	(d)			
Ge	0.78							
As	0.046							
Se	0.32			0.32	(d)			
Br	0.83							
Rb	5.6	5.32	(b)		5.7	(d)		
Sr	45	38	(b)					
Y		13.55	(b)					
Zr	73	61.01	(b)					
Nb	5.5	3.93	(b)					
Mo			0.0636	(d)				
Pd ppb	1.8							
Ag ppb	27		12.4	(d) 31	(d)			
Cd ppb	66			61	(d)			
In ppb	24			22	(d)			
Sb ppb	9			12	(d)			
Te ppb	1.6			1	(d)			
I ppm	<0.005							
Cs ppm	0.36	0.37	(b)		0.38	(d)		
Ba	26	22.3	(b)					
La	1.51	1.44	(b) 2.24	(c)				
Ce	3.75	3.47	(b) 1.95	(c)				
Pr		0.509	(b)					
Nd	2.75	2.53	(b)					
Sm	1.11	0.961	(b) 1.47	(c)				
Eu	0.475	0.399	(b) 0.58	(c)				
Gd		1.56	(b) 0.58	(c)				
Tb	0.28	0.308	(b) 0.497	(c)				
Dy	2.2	2.17	(b)					
Ho		0.479	(b)					
Er	1.6	1.34	(b)					
Tm								
Yb	1.27	1.22	(b) 1.88	(c)				
Lu	0.195	0.186	(b) 0.261	(c)		0.204	0.198	(e)
Hf	1.7	1.54	(b) 1.69	(c)		1.55	1.56	(e)
Ta	0.2	0.19	(b)					
W ppb	610		283	(d)				
Re ppb	0.035				0.0755	(e)		
Os ppb	0.12		0.51	(d)	0.00911	(e)		
Ir ppb	0.03		1.19	(d)				
Au ppb	2		1.37	(d) 2.2	(d)			
Tl ppb	11.6			12	(d)			
Bi ppb	5.1			5.1	(d)			
Th ppm	0.37	0.285	(b)					
U ppm	0.12	0.075	(b)		0.154	(d)		
<i>technique (a) ICP-AES, (b) ICP-MS, (c) INAA, (d) RNAA, (e) IDMS</i>								

Table VI-2. Chemical Composition of amphibole in Zagami.

reference weight %	Treiman 85	Mikouchi 2000
SiO ₂	35.15	35.58
TiO ₂	8.94	9.4
Al ₂ O ₃	15.13	14.68
Cr ₂ O ₃	0.37	0.16
V ₂ O ₃		0.09
FeO	16.18	18.05
MnO	0.29	0.27
CaO	11.48	10.23
MgO	6.4	5.43
Na ₂ O	2.38	1.68
K ₂ O	0.2	0.09
P ₂ O ₅		0.58
F	0.08	
Cl	0	
H ₂ O	1.88	
sum	98.48	

amphibole has been analyzed for D/H ratio by Watson *et al.* (1994c). Using micro-Raman spectroscopy, Mikouchi and Miyamoto (2000) found that the amphibole in Zagami has spectra similar to kaersutite. Treiman (1985) and Mikouchi and Miyamoto (2000) give analyses of amphibole (table VI-2).

Phosphates: McCoy *et al.* (1992) reported whitlockite in Zagami and Wadhwa *et al.* (1994a) found that the REE pattern for whitlockite was similar to that of the bulk sample. Wang *et al.* (1998) determined the Raman spectra of both apatite and whitlockite. Watson *et al.* (1994a) studied a large apatite grain in the residual melt portion of Zagami (DN) (Vistisen *et al.* 1992; McCoy *et al.* 1993; Wadhwa *et al.* 1993b) and found that it contained 0.3-0.4 wt % H₂O with a high D/H ratio. McCoy *et al.* (1999) report that “large” phosphates are abundant in the late-stage melt pockets in the dark, mottled lithology and give analyses.

Sulfides: The sulfide phase is pyrrhotite (Fe_{0.94}S) (McCoy *et al.* 1999).

Oxides: Titanomagnetite occurs as subhedral grains and has minor ilmenite exsolution. Analyses are given in Stolper and McSween (1979) and McCoy *et al.* (1999).

Fayalite: Fayalite (Fo₈₋₁₀) occurs as part of “intergrowth” assemblage in late-stage DN lithology. Wadhwa *et al.* (1993) reported that this late-stage olivine was considerably enriched in Ti, Zr, Y and REEs. Olivine was first noted in Mössbauer spectra by Vistisen *et al.* (1992).

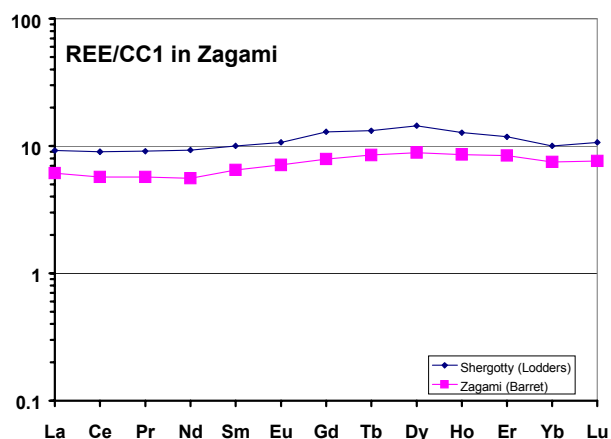


Figure VI-6. Normalized rare-earth-element diagram for Zagami compared with that of Shergotty. The data for Zagami are from Barret *et al.* 2001.

Glass: Glass veins (pseudotachylite) and “glass pods” in Zagami were analyzed by McCoy *et al.* (1992), Marti *et al.* (1995) and Langenhorst and Poirier (2000).

Whole-rock Composition

Easton and Elliot (1977) reported the bulk composition of Zagami and noted a trace of bound water. Stolper and McSween (1979), McCoy *et al.* (1991, 1992), Haramura (1995a), Wang *et al.* (1998), Kong *et al.* (1999) and Barrat *et al.* (2000) have also reported bulk analyses (table VI-1). Trace elements have been determined by Shih *et al.* (1982) and Barret *et al.* 2001. (figure VI-6). Smith *et al.* (1984) noted that there was a wide range of absolute REE abundances (e.g. La = 0.9 to 1.9 ppm), as reported by various investigators. Gibson and Moore (1983) determined 1850 ppm S. Karlsson *et al.* (1992) determined 430 ppm H₂O.

Radiogenic Isotopes

Shih *et al.* (1982) originally determined an age of 180 ± 4 Ma with $I_{Sr} = 0.72145 \pm 5$ using Rb-Sr (figure VI-7) ($\lambda_{Rb} = 1.39 \times 10^{-11} \text{ year}^{-1}$). They also reported an argon plateau age of ~260 Ma for the plagioclase (figure VI-8). Nyquist *et al.* (1995) determined Rb-Sr isochrons of 186 ± 5 Ma and 183 ± 6 Ma for the fine and coarse grained portions of Zagami and found a slight difference in the initial Sr of the two lithologies. Nyquist *et al.* (1995) determined the Sm-Nd isochron using data from both lithologies to give an age of 180 ± 37 Ma. Bogard and Garrison (1998) recalculate the Ar39-40 age as 209 Ma.

By leaching “whole rock” samples of Zagami, Chen and Wasserburg (1986a) obtained a U-Pb “isochron

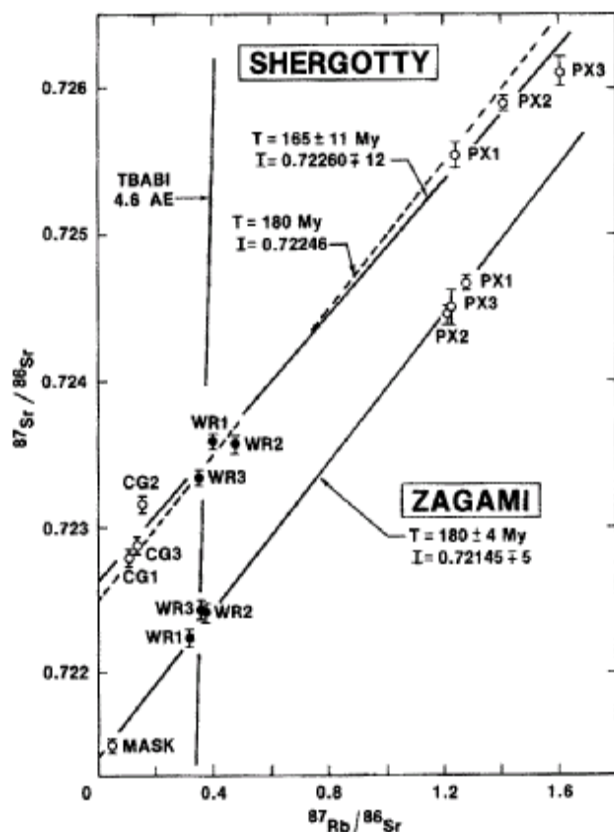


Figure VI-7. Rb-Sr isochron diagram for Zagami and Shergotty meteorites. This is figure 3 in Shih *et al.* 1982, *GCA* 46, 2323.

age” of 230 ± 5 Ma (see figure V-10) and a Th-Pb “isochron” of 229 ± 8 Ma (see figure V-11). These leach experiments probably attack the phosphates in the sample, which may have already been altered on Mars.

Borg *et al.* (2003) have determined the U/Pb systematics of Zagami, and find that the whole rock and mineral separates fall along a line that intersects concordia at 163 ± 4 Ma and at 4550 ± 10 Ma, consistent with the interpretation that the source region for Zagami magma was originally formed very early and was differentiated only once, at the time of basalt formation 163 Ma (consistent with crystallization ages).

Cosmogenic Isotopes and Exposure Ages

Bogard *et al.* (1984b) measured cosmic-ray produced ^3He , ^{21}Ne and ^{38}Ar and determined the exposure age to be ~ 2.5 Ma. Pal *et al.* (1986) determined an exposure age of 5.3 ± 3.5 Ma using ^{10}Be . Eugster *et al.* (1996) derived an exposure age for Zagami of 2.8 ± 0.2 Ma and concluded that Zagami was “ejected from Mars simultaneously with the other basaltic shergottites,

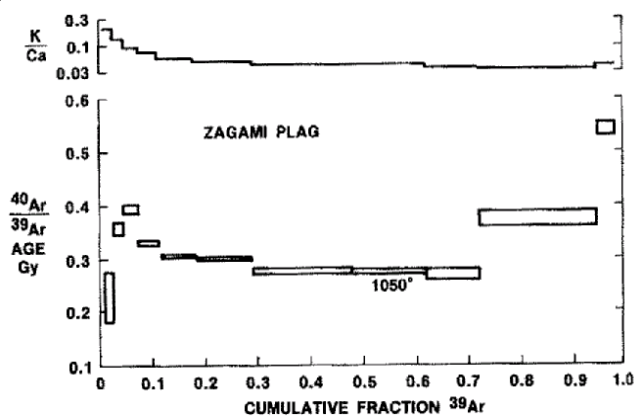


Figure VI-8. Ar plateau diagram for Zagami meteorite from Shih *et al.* 1982, *GCA* 46, 2330.

Shergotty and QUE94201.” Terribilini *et al.* (2000) and Eugster *et al.* (2002) used ^{81}Kr to determine 3.05 Ma and 2.98 ± 0.3 Ma (respectively). Nyquist *et al.* (2001) average these data to get an “average exposure age” of 2.92 ± 0.15 Ma.

Since Zagami fell in 1962, its terrestrial age is now 40 yr.

Other Isotopes

Clayton and Mayeda (1983, 1996) and Franchi *et al.* (1999) have reported the oxygen isotopes for Zagami. Karlsson *et al.* (1992) found that the oxygen isotopes in water released from Zagami was enriched in ^{17}O , indicating that the past hydrosphere on Mars was from a different reservoir than the lithosphere. Romanek *et al.* (1996, 1998) reported additional oxygen isotope data, using a new laser technique. It would appear that Weichert *et al.* (2001) have determined $\Delta^{17}\text{O}$ with superior precision.

Watson *et al.* (1994c) reported the deuterium contents of hydrous amphiboles and a large apatite in Zagami. Leshin *et al.* (1996) found the water released from Zagami had high D/H ratios (see figure V-12).

Fallick *et al.* (1983), Wright *et al.* (1986), Jull *et al.* (1996b) and Grady *et al.* (1997) have reported measurements of carbon isotopes from Zagami. Jull reported the measurements with low ^{14}C (a measure of terrestrial contamination) have $\delta^{13}\text{C} = -20$ ‰. Grady *et al.* found C and N released above 600°C was of magmatic origin with $\delta^{13}\text{C} \sim -26$ ‰ and $\delta^{15}\text{N} \sim -5$ ‰. Grady *et al.* reported that the carbon and nitrogen released below about 600°C , was probably from terrestrial organic contamination.

Blichert-Toft *et al.* (1998, 1999) determined the isotopic ratio of Hf, Harper *et al.* (1995) determined the isotopic ratio of Nd, Lee and Halliday (1997) determined the isotopic ratio of W, and Molini-Velsko *et al.* (1986) reported normal isotopic composition for Si. Hidaka *et al.* (2001) have studied the isotopic composition of Gd and Sm to understand neutron capture effects. Brandon *et al.* (2000) studied the Re-Os isotopic systematics and modeled Zagami with crustal contamination.

Chen and Wasserburg (1986a) reported the Pb isotopes in Zagami and concluded that the parent body (Mars) was enriched in ^{204}Pb and other volatiles.

Marti *et al.* (1995) reported the isotopic signatures of nitrogen, argon and xenon in shock-melted glass “pockets” in Zagami and found the same characteristics (heavy nitrogen) as for the glass from EETA79001 and Viking (figure VI-9). This was the second Martian meteorite (besides EETA79001) found to contain trapped (modern) Martian atmosphere.

Schnabel *et al.* (2001) have reported the activity of ^{10}Be , ^{26}Al and ^{53}Mn .

Shock Effects

Zagami contains thin veins and pockets of black glass produced by shock (McCoy *et al.* 1992; Langenhorst and Poirier 2000). Stöffler *et al.* (1986) determined that the shock pressure and peak temperature experienced by Zagami was 31 ± 2 GPa and 220°C . Marti *et al.* (1995) studied the shock-melted pockets in the mottled lithology. Langenhorst *et al.* (1991)

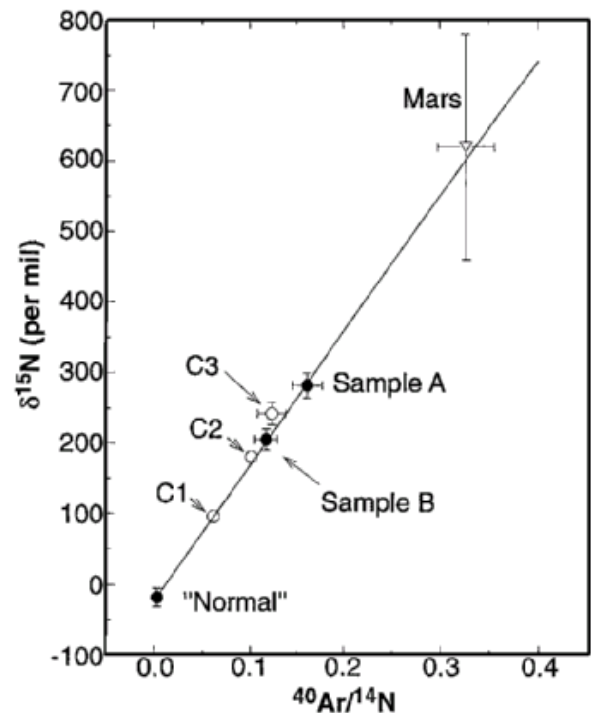


Figure VI-9. Nitrogen isotopic composition nad N/Ar ratio of gas released from glass inclusions in Zagami meteorite compared with data from Viking and EETA79001. This is figure 3 in Marti *et al.* 1995, *Science* **267**, 1983.

carefully studied the maskelynite (see above). Mikouchi *et al.* (1998) report annealing experiments on “maskelynite” from Zagami and find that it is not a diaplectic glass, but rather melted plagioclase.. Langenhorst and Poirier (2000a, b), El Goresy *et al.* (2000) and Malavergne *et al.* (2001) reported various “high-pressure phases” (omphacite, hollandite, stishovite, “post-stishovite silica”, “silicate ilmenite”,

Table VI-3. Petrophysical properties of SNC meteorites.
(from Terho 1996)

Meteorite	NRM	χ_0	Q	ρ	Ref.
Chassigny	19	14	3.22	3319	3
Nakhla	13	182	0.18		1,2
Governador Valadares	51	167	0.76		1,2
Shergotty A-B	41	127	0.81		1,2
Shergotty C	361	112	8.1		1,2
Zagami fc	260	100	6.5		1,2
Zagami	4069	54	188	3071	3
ALHA77005,77	32	645	0.12		1,2
ALHA77005	23	347	0.17		4
EETA79001 A	17	88	0.48		1,2
EETA79001	30	47	1.6		4
EETA79001,183	24	63	0.95	3124	3

NRM = natural remanent magnetization (10^{-6} Am²/kg)

χ_0 = initial susceptibility (10^{-8} m³/kg)

Q = Koenigsberger ratio

ρ = density (kg/m³)

References: 1) Cisowski 1985, 2) Cisowski 1986, 3) Terho *et al.* 1993, 4) Collinson 1986.

Table VI-4. Magnetic properties (from Rochette *et al.* (2001), *EPSL* 190, 2).

Sample	χ_{lr}	χ_{hr}	M_{rs}	M_s	M_{rs}/M_s	S ratio	B_c	B_{cr}		MDF _i	MDF _n	REM
Basaltic Shergottites												
Shergotty	811	476	31.3	81.5	0.38	−0.72	62	113	<i>149</i>	107	86	0.52
Zagami	525	399	7.5	20.9	0.36	−0.83	60	97	<i>143</i>	122	83	0.15
DaG 476 a/b	857/944	358/351	20.3/21.9	59.5/60.2	0.34/36	−0.86	39/42	88/93	<i>93</i>	56/59	18/12	0.8/0.3
DaG 489	929	326	20.9	58.4	0.36	−0.85	43	98	<i>99</i>	71	95	55
DaG 670	816	380	11.4	36.4	0.31	−0.82	33	100	—	76	85	60
Dho 019	633	430	23.1	63.5	0.36	−0.87	51	81	76	46	8	0.31
SAU 005 s/l	786/768	295	4.63/4.78	21.2	0.22	−0.63	21	92	<i>99</i>	71/78	45	0.04/0.7
LA 1 s/l	10300/2690	719	609/110	1232	0.49	−1.00	39	55	<i>48</i>	31	26/65	26/9
Nakhla	1609	420	72	237	0.30	−0.97	34	61	<i>66</i>	33	22	0.11
Chassigny	562	554	0.73	6.8	0.11	−0.95	27	63	<i>61</i>	36	> 120	0.07

When two subsamples have been measured (e.g. a/b), the two values are separated by a slash; otherwise the first sample only is measured. Low- and high-field susceptibility (in 10^{-9} m³/kg): χ_{lr} and χ_{hr} . Saturation remanent and induced magnetization (in 10^{-3} Am²/kg): M_{rs} and M_s . Induced and remanence coercive force B_c , and B_{cr} in mT (using 1 T with VSM, or 2.7 T with 2G if in italics), median destructive field (MDF in mT) of IRM (0.9 T) and NRM, REM ratio (NRM/IRM) in %.

“silicate perovskite”, “silicate titanite”) in Zagami. These recent studies, using TEM analysis, indicate a substantially higher shock pressure. Weber *et al.* (2000) could not find “post-stishovite silica”, but instead reported silica lamellae interstitial between, or included within, maskelynite. Boctor *et al.* (2001) found silica with substantial water content (*and there appears room for much debate*).

Experiments

Dreibus *et al.* (1996a) have reported experiments on leaching Zagami, showing that the phosphates readily dissolve, releasing many trace elements in solution.

Stolper and McSween (1979), McCoy and Lofgren (1996, 1999), and Mikouchi *et al.* (1999), have

performed crystallization experiments to determine the phase equilibria and cooling history.

The infrared spectra of various lithologies of Zagami has been measured by Hamilton and Christensen (1996), Wäsch and Schade (1996), Hamilton *et al.* (1997) and Schade and Wäsch (1999). Wang *et al.* (1998, 1999) used Raman spectroscopy to determine the mineralogical mode!

The magnetic properties of Zagami have been studied by Cisowski (1985, 1986), Terho *et al.* (1996, 1998) (table VI-3), Collinson (1997) and Rochette *et al.* (2001). Rochette *et al.* (see Table VI-4 above) observed that natural magnetic remanence is carried by pyrrhotite (*easily reset by shock pressures that Martian meteorites*

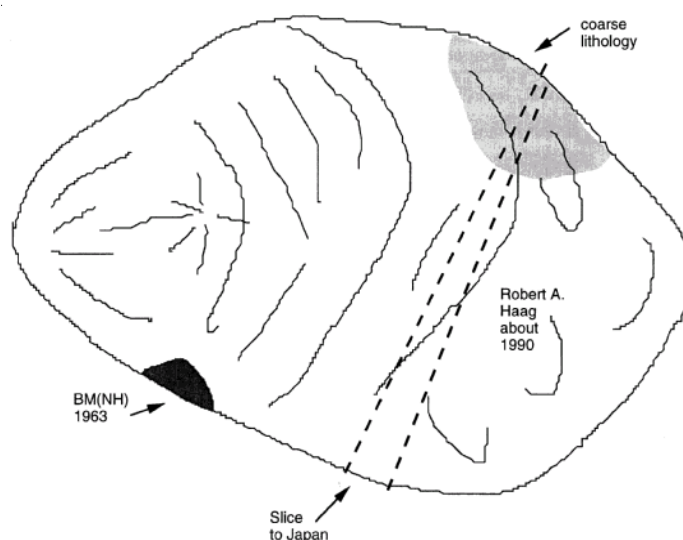


Figure VI-10. Sketch of Zagami provided by R. Haag who witnessed the sawing of the sample in 1988. The coarse lithology is referred to in the text as the DML lithology. The sample obtained by the British Museum in 1963 is known as normal Zagami (NZ) and seems to be representative of the main mass.

must have experienced).

Processing

In 1963, the main mass of Zagami was sent to the British Museum of Natural History. In 1965, it was returned to Kaduna, Nigeria. In 1985, the meteorite catalog of Graham *et al.* showed that the BM(NH) had pieces weighing 234 grams - with the main mass in Kaduna. The fifth revision of the BM Catalog (Grady 2001) shows the current locations of the pieces of Zagami. In 1978, Nyquist obtained a 13 gram piece from Nigeria, that was sawn on three sides illustrating a gradational contact from fine to coarse grain basalt (figure VI-2), including a thin black glass vein (Nyquist, personal communication).

About 1988, the main mass was sawn to reveal the interior (?). Robert Haag (meteorite dealer) was apparently able to trade “a complete meteorite collection” for a sizable portion of the Zagami stone (Norton 1994). Haag (1991) illustrated a piece 158 x 165 x 70 mm weighing 2.8 kg partially covered by fusion crust. Since 1991, the main mass in Kaduna has apparently been further cut up and “distributed” (figures VI-10 and VI-11) (Haag, personal communication).

During his visit to Nigeria, Haag met the man who witnessed the fall (Haag 1991). “He was trying to chase the cows out of his corn field when he heard a tremendous explosion and was buffeted by a pressure wave. Seconds later, there was a puff of smoke and a thud, as something buried itself in the soft dirt only ten feet away. Terrified that it was an artillery shell or bomb, the man waited for a few minutes before going to investigate. What he saw was a black rock at the bottom of a two-foot hole. The local commissioner was summoned and the specimen was recovered and sent to the provincial capital, where it was placed in the museum.”

McCoy *et al.* (1992) reported on two pieces weighing 19.5 grams (coarse grain) and 354 grams (fine grain) that were used for a consortium study led by Tim McCoy and Klaus Keil. The smaller piece is a sawn slab, 5 x 3 x 0.4 cm and contained “glassy pockets”. The larger piece is roughly cubic, 5 cm on a side, with a glassy fusion crust on one side.

McCoy *et al.* (1995) reported examination of a ~910 cm² of sawn surface area of Zagami which “revealed that DN was not present in the normal Zagami (NZ)

lithology described by (McCoy et al. 1992; Treiman and Sutton 1992), but rather in a volumetrically significant lithology termed the dark, mottled lithology (DML). DML occupies ~20% of Zagami and borders NZ along a sharp, but sometimes irregular, boundary.”

The original piece of the DN lithology (~1 cm) was obtained by Vistisen and coworkers from David New (meteorite dealer). All four Zagami lithologies (NZ, DML, DN and melt pockets) are present in Smithsonian sample USNM 6545 (McCoy, personal communication).



Zagami

Zagami, cut and quartered

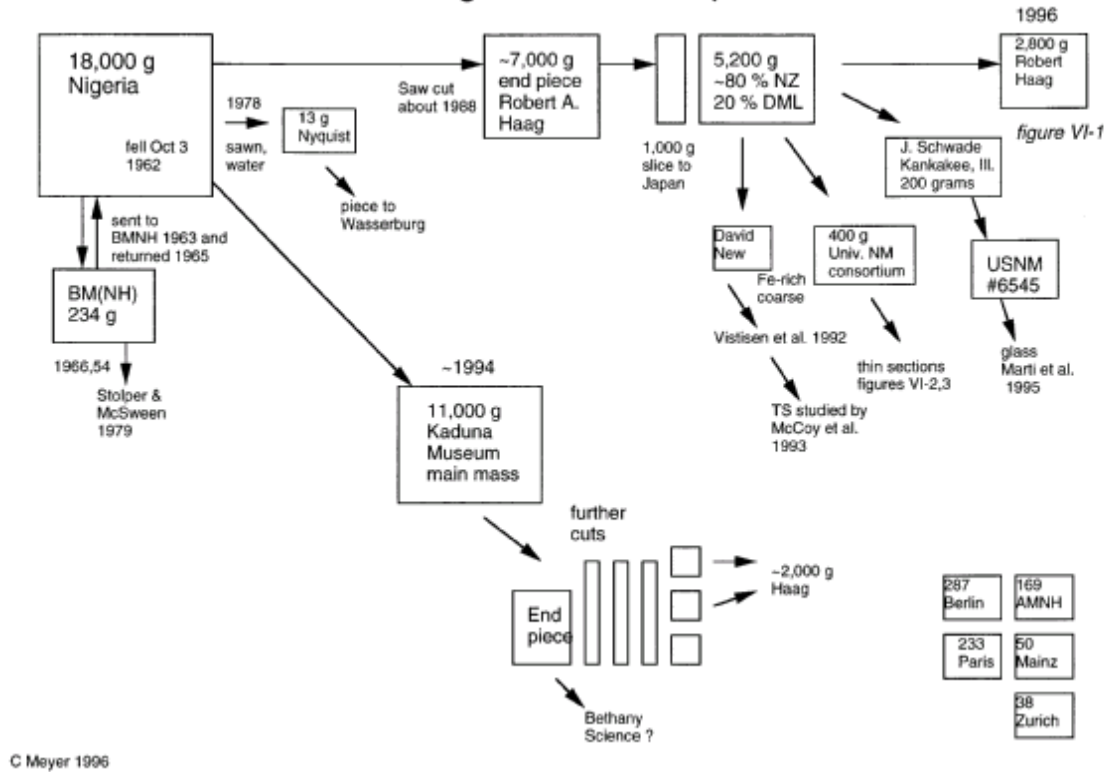


Figure VI-11. Schematic illustration of cutting and distribution of Zagami meteorite. See Grady 2000 for more information.